

Chiral symmetry and meson exchange approach to hypernuclear decay

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Abstract

We take an approach to the Λ nonmesonic weak decay in nuclei based on the exchange of mesons under the guidelines of chiral Lagrangians. The one pion and one kaon exchange are considered, together with the exchange of two pions, either correlated, leading to an important scalar-isoscalar exchange (σ -like exchange), or uncorrelated (box diagrams). A drastic reduction of the OPE results for the Γ_n/Γ_p ratio is obtained and the new results are compatible with all present experiments within errors. The absolute rates obtained for different nuclei are also in fair agreement with experiment.

[Key Word] Λ weak decay, Γ_n/Γ_p ratio, chiral unitary theory.

1 Introduction

The problem of the Γ_n/Γ_p ratio is the most persistent and serious problem related to the nonmesonic decay of Λ hypernuclei. The OPE model, using exclusively the parity conserving part of the weak Λ decay vertex $H_{\Lambda\pi N}$ leads to a Γ_n/Γ_p ratio of 1/14 [1] in nuclear matter. If in addition one includes the parity violating term, which is less important than the parity conserving one for the nonmesonic decay, the ratio changes to about 1/8 [2, 3].

Experimentally one has results for ${}^5_\Lambda\text{He}$ from [4] with a ratio 0.93 ± 0.5 and for ${}^{12}_\Lambda\text{C}$ with ratios $1.33^{+1.12}_{-0.81}$ [4], $1.87^{+0.91}_{-1.59}$ [5] and 0.70 ± 0.30 , 0.52 ± 0.16 [6]. More recent results for ${}^{12}_\Lambda\text{C}$ are still quoted as preliminary [7, 8] but also range in values around unity with large errors.

The large discrepancy of the OPE predictions with the experimental data has stimulated much theoretical work. One line of progress has been the extension of the one meson exchange model including the exchange of $\rho, \eta, K, \omega, K^*$ in [2] and [3]. The results obtained are somewhat contradictory since while in [2] values for the Γ_n/Γ_p ratio around 0.83 are quoted for ${}^{12}_\Lambda\text{C}$, the number quoted in [3] is 0.07. Also, in [3] the same ratio is obtained for ${}^5_\Lambda\text{He}$ and ${}^{12}_\Lambda\text{C}$ while in [2] the value of the ratio in ${}^{12}_\Lambda\text{C}$ is about twice larger than for ${}^5_\Lambda\text{He}$ (see [9] for a further discussion on this issue).

Another line of progress has been the consideration of two pion exchange. An early attempt in [10] including N and Σ intermediate states in a box diagram with two pions did not improve on the ratio and it made it actually slightly worse. However, in [11] the Δ intermediate states were also considered leading to an increase of the Γ_n/Γ_p ratio, although no numbers were given. A close line was followed in [12, 13] where the exchange of two interacting pions through the σ resonance was considered and found to lead also to

improved results in the Γ_n/Γ_p ratio. Although there are still some differences in the works and results of [12, 13] (see [9] for details) they share the qualitative conclusion that the Γ_n/Γ_p ratio increases when the σ exchange is considered. In [12] the ratio goes from 0.087 for only pion exchange to 0.14 when the correlated two pions in the σ channel (and also the ρ , which does not change much the ratio) are considered.

Quark model inspired work leads to higher values for the Γ_n/Γ_p ratio from the contribution of short distances but the total rates are overpredicted [14, 15, 16].

The situation is hence puzzling. Discrepancies between authors using the similar approach still persist, but in spite of that, there is a clear discrepancy between predictions of different models and present experimental results.

In the present talk I report on the recent work [17], where in addition of the one pion exchange we have considered kaon exchange and correlated as well as uncorrelated two pion exchange. The correlated two pion exchange has been done here following closely the steps of the recent work [18] where the two pions are allowed to interact using the Bethe-Salpeter equation and the chiral Lagrangians [19]. This chiral unitary approach to the pion pion scattering problem leads to good agreement with the $\pi\pi$ data in the scalar sector including the generation of a pole in the t-matrix corresponding to the σ meson [20].

The results obtained here lead to ratios of Γ_n/Γ_p of the order of 0.4 and simultaneously one can obtain fair agreement for the absolute rates of different nuclei. These relative high values obtained for Γ_n/Γ_p are compatible with all present experiments within errors, if these errors are enlarged as suggested in [23] and [24].

2 One Pion Exchange

The decay of the Λ in nuclear matter was investigated with the propagator approach which provides a unified picture of different decay channels of the Λ [25]. The decay width of the Λ is calculated in infinite nuclear matter, and is extended to finite nuclei with the local density approximation. In this section we shall review the calculation of the decay width of the Λ in nuclear matter using the one pion exchange approach.

First of all, we start with an effective $\pi\Lambda N$ weak interaction which is written,

$$\mathcal{L}_{\Lambda N\pi} = iG\mu^2\bar{\psi}_N[A + \gamma_5 B]\vec{\tau} \cdot \vec{\phi}_\pi\psi_\Lambda + \text{h.c.} \quad (1)$$

where μ denotes the pion mass, and G is the weak coupling constant with

$$G\mu^2 = 2.211 \times 10^{-7} \quad (2)$$

By assuming that the Λ behaves as a $I = 1/2, I_z = -1/2$ state in the isospin space, this effective interaction already implements the phenomenological $\Delta I = 1/2$ rule, which is seen in the nonleptonic free decay of the Λ . The coupling constants A and B are determined by the parity conserving and parity violating amplitudes of the nonleptonic Λ decay, respectively:

$$A = 1.06, \quad \frac{B}{2M_N}\mu = -0.527 \quad (3)$$

with M_N the nucleon mass. The πNN vertex with strong interaction is given by the following effective Lagrangian:

$$\mathcal{L}_{\pi NN}^S = -\frac{D+F}{2f_\pi}\bar{\psi}_N\gamma^\mu\gamma_5\vec{\tau} \cdot \partial_\mu\vec{\phi}_\pi\psi_N \quad (4)$$

with $D + F = 1.26$ and $D - F = 0.33$.

In order to evaluate the Λ decay width Γ , in a nuclear medium due to a certain $\Lambda N \rightarrow NN$ transition amplitude, we start with the calculation of the self-energy in the medium, Σ , shown in fig.1, and then we take its imaginary part:

$$\Gamma = -2 \text{Im } \Sigma \quad (5)$$

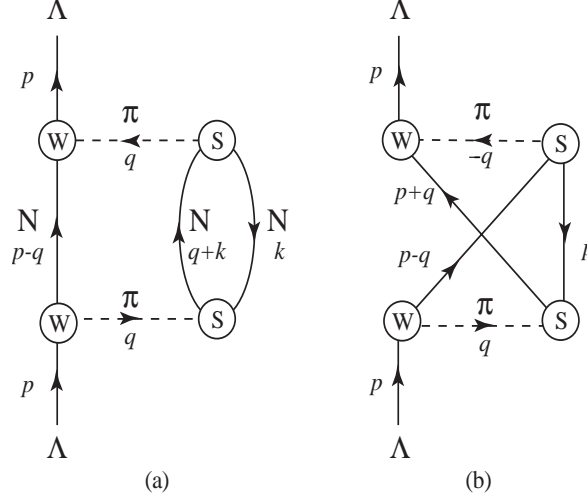


Figure 1: Lowest order of self-energy of Λ . The nonmesonic width comes from the imaginary part when the intermediate states cut by a horizontal line are placed on shell.

In addition we take into account the ph and Δh excitations to all orders in the sense of the random phase approximation (RPA) as done in [25].

On the other hand, short range correlations are also introduced following [25] and they modulate the $\Lambda N \rightarrow NN$ transition amplitude. In terms of the Landau-Migdal parameter, our value for g' of the strong spin-isospin interaction has a strength of 0.7 at $\vec{q} = \vec{0}$ and a \vec{q} dependence as given in [25].

In fig. 2 we can see the direct and exchange diagrams which contribute to the Λ decay induced by protons or neutrons. The representation is useful to see the effects of the isospin in the Γ_n/Γ_p rates. First let us note that the momentum of the pion in the upper pion of the exchange diagram is $-\vec{q}$ going to the left (neglecting Fermi motion), while in the direct diagram the momentum is \vec{q} . This has as a consequence that the relative sign of the parity conserving versus parity violating terms in the upper pion exchange is opposite for the exchange diagram than for the direct one. As a consequence a simple counting of the rates is possible simply taking into account the isospin coupling of the vertices ($\sqrt{2}$ for charged pions, 1 for the $\pi^0 pp$ vertex and -1 for the $\pi^0 nn$ vertex). We find the ratios for the parity conserving and parity violating parts:

Parity conserving:

$$\frac{\Gamma_n}{\Gamma_p} = \frac{1 - \frac{1}{2}}{1 + 4 + 2 \frac{1}{2} + 2 \frac{1}{2}} = \frac{1}{14} \quad (6)$$

Parity violating:

$$\frac{\Gamma_n}{\Gamma_p} = \frac{1 + \frac{1}{2}}{1 + 4 - 2 \frac{1}{2} - 2 \frac{1}{2}} = \frac{1}{2} \quad (7)$$

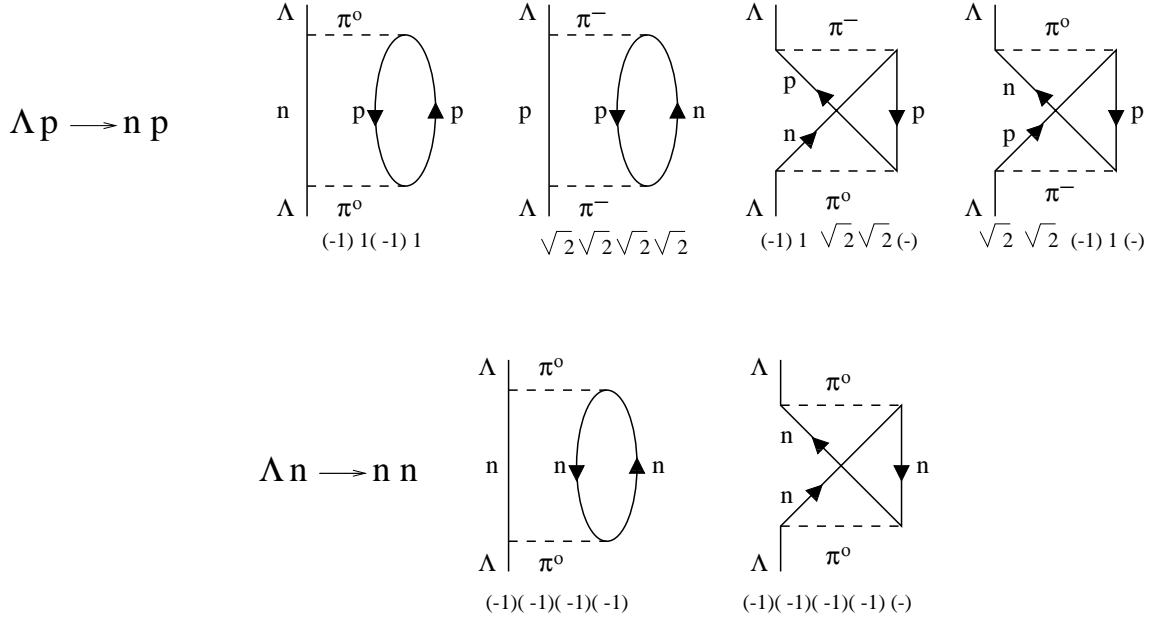


Figure 2: The isospin factors of the direct and exchange terms induced by proton and neutron.

And given the weight of the parity conserving and parity violating parts one finds finally a ratio Γ_n/Γ_p around 1/8. The ratio is too large and the absolute rates, of about $\Gamma = 2\Gamma_\Lambda$ are too large compared with experiment.

3 Kaon Exchange

The non-mesonic decay of Λ with one K exchange takes place through the diagram shown in fig. 1 substituting the pions by kaons in the figure. The inclusion of the K exchange is straightforward in the meson propagator approach, once the KNN weak vertex is fixed.

The strong $K\Lambda N$ vertex is given by:

$$\mathcal{L}_{K\Lambda N}^S = f_{K\Lambda N} \bar{\psi} \gamma^\mu \gamma_5 \partial_\mu \phi_K \psi_\Lambda + \text{h.c.} \quad (8)$$

which is estimated with the $SU(3)$ flavor symmetry:

$$f_{K\Lambda N} = \frac{D + 3F}{2\sqrt{3}f_\pi} \quad (9)$$

Note that there is a different sign in $f_{K\Lambda N}$ with respect to the $pp\pi^0$ vertex of eq. (4).

The weak vertex of NNK may be written as

$$\begin{aligned} \mathcal{L} = & iG\mu^2 \left[\bar{\psi}_p (A^{K^0,p} + \gamma_5 B^{K^0,p}) \phi_{K^0}^\dagger \psi_p \right. \\ & + \bar{\psi}_p (A^{K^-,p} + \gamma_5 B^{K^-,p}) \phi_{K^-}^\dagger \psi_n \\ & \left. + \bar{\psi}_n (A^{K^0,n} + \gamma_5 B^{K^0,n}) \phi_{K^0}^\dagger \psi_n \right] + \text{h.c.} \end{aligned} \quad (10)$$

Equation (10) shows the parity conserving (B coefficients) and parity violating terms (A coefficients) for the case of the kaon weak coupling. The parity violating terms can be

deduced following [2] by means of current algebra arguments assuming that they behave like the sixth component of the SU(3) generators or equivalently using appropriate chiral Lagrangians. On the other hand the parity conserving part does not follow this symmetry and some models have to be done. We have used the results of the pole model used in [2]. As we shall see, the kaon exchange, through interference with the pions, leads both to higher Γ_n/Γ_p ratios and also smaller total rates.

4 Two-pion exchange

Another kind of diagrams that have been traditionally studied are those corresponding to two-pion exchange. We will divide the study of these diagrams into two categories: correlated two-pion exchange and uncorrelated two-pion exchange. In the case of correlated exchange we will only consider the scalar- isoscalar channel, where the σ meson appears. The vector channel is neglected since the ρ contribution has been seen to be not too relevant [13]. We will see that the scalar-isoscalar channel is also the relevant one in the case of uncorrelated two-pion exchange. The effect of heavier scalar mesons (such as the f_0, a_0) is also found negligible in [13] and is neglected here.

4.1 Correlated two-pion exchange

Some works on this topic have been done [12, 13, 26], incorporating the σ meson as an explicit degree of freedom. There it is found that, working with reasonable values for the mass, width and $\sigma\pi\pi$ coupling, the role of this " $2\pi/\sigma$ " exchange is relevant in the non-mesonic decay problem.

A less phenomenological treatment of the sigma meson is provided by the Chiral Unitary Approach [20, 27, 28]. In [20] it was found that the σ meson is dynamically generated by the in-flight two pion interaction when summing up the s-wave t -matrix of the $\pi\pi$ scattering to all orders using the Bethe-Salpeter equation. The former picture of the σ meson was used to describe its role in the NN interaction in ref. [18], finding a moderate attraction beyond $r = 0.9$ fm and a repulsion at shorter distances, in contrast with the all attraction of the conventional σ exchange. We will follow an analogous model to the one of the aforementioned reference.

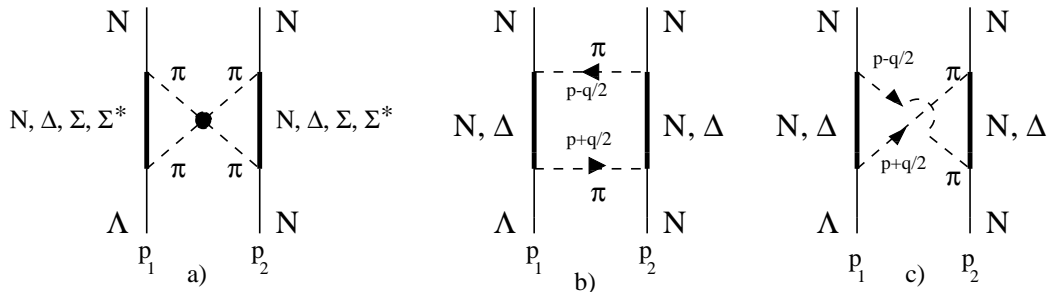


Figure 3: Diagrams corresponding to two-pion exchange: a) correlated exchange; b) uncorrelated exchange: direct diagram; c) uncorrelated exchange: crossed diagram.

The diagrams corresponding to the correlated exchange are those of fig. 3a). In the weak vertex we will only consider the parity conserving term of the lagrangians since it is the relevant one when dealing with loops. This simplifies the problem because, as the

parity conserving part (proportional to $\vec{\sigma}\vec{q}$, where \vec{q} is the momentum of the pion) has the same structure as the πNN interaction, the results obtained in ref. [18] are also applicable here. One is then allowed to take the expression of the potential coming from the diagrams with N and Δ as intermediate states from that reference, with the only difference of a multiplicative factor \mathcal{R} that reflects the replacement of one strong πNN vertex by the weak $\Lambda\pi N$. The potential is then given by [18]:

$$t_{\Lambda NNN}(q) = \mathcal{R} \tilde{V}^2(q) \frac{6}{f^2} \frac{\vec{q}^2 + \frac{m_\pi^2}{2}}{1 - G(-\vec{q}^2) \frac{m_\pi^2}{2} f^2} \quad (11)$$

where $G(s)$ is the loop function with two pion propagators, and the vertex function $\tilde{V}(q)$ and \mathcal{R} are given by:

$$\begin{aligned} \mathcal{R} &= \frac{G\mu P}{\frac{D+F}{2f_\pi}} \\ \tilde{V}(q) &= \tilde{V}_N(q) + \tilde{V}_\Delta(q) \end{aligned} \quad (12)$$

So far we have been studying diagrams in which the Λ baryon appears in the weak vertices. However, as we can see in figure 3a), there are also diagrams with a strange intermediate baryon (Σ, Σ^*) strongly coupled to the Λ and the weak vertex in the upper side of the diagram. We have evaluated them using SU(3) symmetry arguments and found an approximate cancellation between the Σ and Σ^* contributions.

As one can see in eq. (11) the sign of the σ potential in momentum space is positive. This is in contrast with any evaluation of the scalar-isoscalar potential taking only the exchange of a σ particle. Indeed one obtains in that case the vertex squared times the σ propagator, and the latter is always negative for the space like situation which one has here. Thus, the chiral approach to σ exchange leads to an opposite sign than the ordinary σ exchange contribution.

4.2 Uncorrelated two-pion exchange

The other set of processes that we have to study when considering the two-pion exchange is the one in which the exchanged pions only interact with baryonic legs and not with other pions (uncorrelated exchange). The corresponding Feynman diagrams are depicted in figs. 3b) and 3c).

We do not include the diagrams with an intermediate Σ and Σ^* , because one expects a similar cancellation to the one found in the correlated exchange, nor the diagrams with two nucleon propagators in diagram a), which correspond to final state interaction and are included in the correlations. We also neglect the spin dependent term, which is found to be negligible.

5 Results

We show the results for ^{12}C separating the different contributions. In table 5 we show the results obtained with only one pion, one kaon or two pion exchange. In addition we write there the contributions when the kaon and the two pion cotributions are added coherently.

	π	K	2π	$\pi + K$	$\pi + K + 2\pi$
Γ_p/Γ_{free}	0.9557	0.2527	0.1905	0.5215	0.5714
Γ_n/Γ_{free}	0.1194	0.1180	0.0903	0.2728	0.3078

Table 1: π , K , 2π contributions together with the combinations of $\pi + K$, $\pi + K + 2\pi$ to the proton- and neutron-induced decay of ${}^{12}_{\Lambda}\text{C}$.

While K or 2π contributions by themselves are small compared to Γ_p from OPE, the interference effects with the OPE contribution are large. We can see that the introduction of the kaon exchange reduces the proton rate by about a factor two and increases the neutron rate also by about a factor two, thus increasing the ratio in about a factor four and reducing the total rate. The additional effects of the two pion contribution are small in both rates as a consequence of some cancellations. It is worth recalling, as we mentioned above, that the σ and uncorrelated 2π contributions have different signs and there are large cancellations between them at the relevant momentum $q \sim 420$ MeV/c. Let us stress once more that we obtain a sign for the σ exchange here which is opposite to the conventional one. Should we have the σ contribution with opposite sign to ours and about the same strength, the combination of σ and uncorrelated two-pion exchange would give a contribution for the 2π part alone about 6 times bigger than here, and this would render the total rates unacceptably large in spite of the interference terms, which are only multiplied by a factor 2.5.

In table 5 we present the results for Γ_p , Γ_n and the Γ_n/Γ_p ratio for different nuclei. We find that the total rates from the $1p1h$ channel go from $\Gamma/\Gamma_{free} = 0.88$ to 1.48 in ${}^{208}_{\Lambda}\text{Pb}$ and the ratios Γ_n/Γ_p are all of them of about $\Gamma_n/\Gamma_p \sim 0.54$.

Nucleus	Γ_p/Γ_{free}	Γ_n/Γ_{free}	$(\Gamma_p + \Gamma_n)/\Gamma_{free}$	Γ_n/Γ_p	$\Gamma_{tot}/\Gamma_{free}$
${}^{12}_{\Lambda}\text{C}$	0.5714	0.3078	0.8792	0.54	1.3992
${}^{28}_{\Lambda}\text{Si}$	0.7562	0.4080	1.1642	0.54	1.5342
${}^{40}_{\Lambda}\text{Ca}$	0.7866	0.4245	1.2111	0.54	1.5411
${}^{56}_{\Lambda}\text{Fe}$	0.8554	0.4620	1.3174	0.54	1.6174
${}^{89}_{\Lambda}\text{Y}$	0.8908	0.4813	1.3721	0.54	1.6721
${}^{139}_{\Lambda}\text{La}$	0.8702	0.4697	1.3399	0.54	1.6399
${}^{208}_{\Lambda}\text{Pb}$	0.9640	0.5195	1.4835	0.54	1.7835

Table 2: Decay rates and the Γ_n/Γ_p ratio for different hypernuclei. In Γ_{tot} we have included the contributions from the mesonic decay and the $2p2h$ channel.

If we want to compare these results with experimental data we should still add the mesonic contribution and the $2p2h$ induced one. For the mesonic contribution we take the results from [30] which agree well with experiment in the measured cases. The mesonic rates are only relevant for the lighter nuclei. We take $\Gamma_M/\Gamma_{free} = 0.25$ for ${}^{12}_{\Lambda}\text{C}$, 0.07 for ${}^{26}_{\Lambda}\text{Si}$ and 0.03 for ${}^{40}_{\Lambda}\text{Ca}$ and neglect this contribution for heavier nuclei. The $2p2h$ induced contribution calculated in [22] is 0.27 for ${}^{12}_{\Lambda}\text{C}$ and 0.30 for the rest of the nuclei. With these results we compute the total rates which we show in table 2. The present status of the lifetime measurements can be found in table 5. We can see that our total rates are about 15% bigger than the experimental numbers in the best measured nuclei. In heavy nuclei

the experimental errors are larger and our results are compatible with the experiment.

Nucleus	Γ/Γ_{free}	Experiment
${}^1_1\text{B}$	$1.37 \pm 0.17[31, 32]$	(K^-, π^-)
	$1.25 \pm 0.08[33]$	(K^+, π^+)
${}^{12}_\Lambda\text{C}$	$1.25 \pm 0.19[31, 32]$	(K^-, π^-)
	$1.14 \pm 0.08[33]$	(K^+, π^+)
${}^{28}_\Lambda\text{Si}$	$1.28 \pm 0.08[33]$	(K^+, π^+)
${}_\Lambda\text{Fe}$	$1.22 \pm 0.08[33]$	(K^+, π^+)
$\bar{p}+{}^{209}\text{Bi}$	$1.1^{+1.1}_{-0.4}[34]$	Delayed fission
	$1.5 \pm 0.3 \pm 0.5[35]$	Delayed fission
$p+{}^{209}\text{Bi}$	$1.8 \pm 0.1 \pm 0.3[36]$	Delayed fission

Table 3: Experimental values of the total width for different nuclei. The value for ${}_\Lambda\text{Fe}$ represents for the average lifetime of ${}^{55}_\Lambda\text{Mn}$, ${}^{55}_\Lambda\text{Fe}$ and ${}^{56}_\Lambda\text{Fe}$.

As for the Γ_n/Γ_p ratios it looks like our results are still smaller than the experimental ones. However, one word of caution is necessary here. The experimental analyses were done neglecting the $2p2h$ induced channel, but it was observed in [22] that the inclusion of this mechanism in the analysis of the data lead to different values of Γ_n/Γ_p . A formula was given in this reference to correct the results of the old analysis due to the consideration of this induced mechanism, but it assumed that all particles were detected. The formula was corrected in [24] assuming that the slow particles (with energies smaller than about 40 MeV) are not detected. Detailed calculations of the spectra of protons and neutrons from the nonmesonic decay were done in [23] but assuming a ratio of $1p1h$ to $2p2h$ induced strength given by the OPE model alone, which as shown here overcounts the $1p1h$ strength. In view of this we just take the formula of [24] and use it to recalculate the experimental bands. The present bands we have are: $1.33^{+1.12}_{-0.81}[4]$, $1.87^{+0.91}_{-1.59}[5]$, $0.70 \pm 0.30[6]$, $0.52 \pm 0.16[6]$. The lower bounds are 0.52, 0.29, 0.4, 0.36 respectively. Our ratio 0.54 falls within all the error bands, but close to the lower boundary. However, if we use the formula of [24] assuming $\Gamma_{2p2h}/\Gamma_{nm}$ of the order of 0.3 one reduces the lower bounds to values 0.2, 0.14, 0.1, 0.01 and the value obtained by us is well within present experimental ranges.

6 Conclusions

We have evaluated the nonmesonic proton and neutron induced Λ decay rates in nuclei, by including one pion, one kaon, σ and uncorrelated two pion exchange. We found that the contribution of K exchange was essential to reduce the total decay rate from the OPE results and simultaneously increase the value of the Γ_n/Γ_p ratio from values around 0.12 for the OPE to values around 0.54. We also included the σ and uncorrelated two pion exchange and we found some cancellations between them, such that the total contribution of the two pion exchange to the total rate and the Γ_n/Γ_p ratio was small. However, in this result it was very important that the contribution of our correlated scalar-isoscalar two-pion exchange had opposite sign to the conventional contributions taking only the exchange of a σ particle. This change of sign was due to the presence of the Adler zero in the scalar-isoscalar $\pi\pi$ interaction which makes the amplitude change sign below $s = m_\pi^2/2$ which is the case here, where we have s negative.

The total rates obtained are fair, about 15% larger than experiment as an average. The ratios Γ_n/Γ_p are considerably improved with respect to the OPE ones. We have also seen that, once the present experimental data are corrected to account for the $2p2h$ channel the value of 0.54 obtained here for the Γ_n/Γ_p ratio is well within the present experimental boundaries.

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